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For: A METHOD OF FABRICATING AN OPTICAL FIBER WITH CONTROLLED
     TRANSMISSION CHARACTERISTICS

DECLARATION

    I, Andrew Scott Marland, of 35, avenue Chevreul, 92270 BOIS COLOMBES, France, declare that I am well acquainted with the English and French languages and that the attached translation of the specification and claims as originally filed on May 25, 2000 in respect of French patent application number 00/06694 is a true and faithful translation of that document.

    All statements made herein are to my own knowledge true, and all statements made on information and belief are believed to be true; and further, these statements are made with the knowledge that willful false statements and the like so made are punishable by fine or imprisonment, or both, under Section 1001 of Title 18 of the United States Code and that such willful false statements may jeopardize the validity of the application or any document or any registration resulting therefrom.

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Andrew Scott Marland

A METHOD OF FABRICATING AN OPTICAL FIBER WITH CONTROLLED
TRANSMISSION CHARACTERISTICS

The invention relates to optical fibers used in
telecommunications networks in particular, and more
precisely it relates to fabricating optical fibers.

In the art of fabricating optical fibers, it is
known to fabricate preforms whose doping is varied in the
radial direction as a function of the required index
profile in the fiber, and then to draw the preform to
obtain the optical fiber. One conventional preform
fabrication method consists of successively depositing
layers of silica by modified chemical vapor deposition
(MCVD) into a deposit tube to form a preform core and
then to form a sleeve around the deposit tube; the sleeve
is generally deposited onto the preform in such a way
that the outside diameter of the preform is constant.
Other fabrication techniques include outside vapor
deposition (OVD) and vapor axial deposition (VAD). The
resulting preform is then drawn.

For applications in optical transmission systems it
is desirable for the propagation characteristics of the
fiber, for example its chromatic dispersion, to be
closely controlled along the fiber. Dispersion can be
kept constant or it can be varied in a controlled manner
between two opposite values, as proposed for example in
EP-A-0 737 873. The propagation characteristics are a
function of the index profile of the fiber, characterized
by the refractive indices and radii of the layers
deposited by MCVD, OVD, or VAD. Despite the great care
taken in fabricating the preform, it is possible for the
preform to suffer from defects and to be less than
perfectly homogeneous, or more generally not to conform
perfectly to its design values.

Generally speaking, the expression "core radius of a
fiber" means the value of the radius beyond which
variations in the index or the radius relative to its
design value has minimal influence on the propagation

characteristics of the fiber. In other words, it refers
to the outer limit of the profile which defines the
propagation characteristics of the fiber. For example,
for a "stepped index" profile, the core radius is the
outside radius of the index step. For a trapezium and
ring profile the core radius is the outside radius of the
ring. The above definition is transposed to a preform on
the principle of geometrical scaling. It is important to
note that the core radius of a preform defined in this
way can be significantly different from the inside radius
of the deposit tube.

Examples of the above defects are variations along
the preform departing from respective nominal values, in
the diameter of the core of the preform, in the radii of
the deposited layers, or in the outside diameter of the
preform. The defects can also be variations along the
preform in the indices of the various layers of the
preform departing from their design indices. For
example, a 1% to 2% radial increase in the diameter of
the core of the preform for a flat chromatic dispersion
slope fiber can cause variations in chromatic dispersion
of 1 picosecond per nanometer-kilometer (ps/(nm.km)) to
2 ps/(nm.km) at 1550 nm; such variations reduce the
production yield. For dispersion compensated fibers
(DCF) and reverse dispersion fibers (RDF) the variations
in the characteristics of the preform can induce
variations in dispersion of up to 10 ps/(nm.km) at
1550 nm.

WO-A-98 25 861 describes a fiber for soliton
transmission applications, in which the outside diameter
of the fiber varies. It states that dispersion varies
with the diameter of the fiber. In a first embodiment
proposed in that document a preform is formed by
depositing layers having thickness that increases from
one end of the preform to the other. The resulting
conical core of the preform is surrounded with its
cladding before the fiber is drawn. In a second

embodiment described in the document a preform is formed
by depositing layers of constant thickness but with the
proportions of dopant varying. In either case, drawing
the preform produces a fiber of constant diameter whose
5   propagation characteristics vary as a function of
position along the fiber.

The invention proposes a solution to the problem of
controlling the propagation characteristics of an optical
fiber caused by variations in the characteristics of the
10   preform departing from its design characteristics. It
enables preform defects or irregularities to be corrected
finely, thereby enabling fibers to be obtained with
improved control over their propagation characteristics.
It is also simple to put into practice.

15   To be more precise, the invention proposes a method
of fabricating an optical fiber by drawing a preform, the
method including:
- determining variations in the characteristics of
  the preform departing from its design
20   characteristics, and
- modifying the diameter of the fiber during drawing
  as a function of said variations to compensate the
  effect of said variations on the propagation
  characteristics of the fiber.

25   The diameter of the fiber is preferably modified to
compensate the effect of said variations on the
propagation characteristics of the fiber

In one implementation, the preform has constant
outside diameter and the determination step includes
30   measuring the diameter of the core of the preform. In
this case, the diameter of the fiber is modified so that
the relative variation in said diameter is in the
opposite direction to the relative variation in the
diameter of the core of the preform.

35   In another embodiment the characteristics are
geometrical characteristics such as the diameter of the
preform, the radii of the layers of the preform or the

diameter of the core of the preform. The characteristics
can instead or also be optical characteristics such as
the indices of the various layers of the preform.

The modifications to the diameter of the fiber are
preferably less than a predetermined limit value, for
example less than 2 micrometers (μm) or less than ±2% of
the nominal diameter of the fiber.

The invention also provides an optical fiber
obtained by the above method.

Other features and advantages of the invention will
become apparent on reading the following description of
embodiments of the invention, which is given by way of
example only.

To compensate variations in the characteristics of
the preform departing from their design values, the
invention proposes to vary the diameter of the fiber
during drawing. Varying the diameter of the fiber
compensates all or some of the variations in the
characteristics of the preform departing from their
design values. The invention is based on the observation
that limited variations (typically in the range ±1% to
±2%) in the diameter of the fiber compensate defects in
terms of the homogeneity or regularity of the preform and
do not cause any problems from the point of view of
subsequent propagation in the fiber.

Modifying the diameter of the fiber while drawing
the preform re-centers the propagation characteristics in
their specific ranges provided that the geometrical
characteristics (the diameter of the core of the preform,
the radii of the deposited layers, or the outside
diameter of the preform) or the optical characteristics
(for example the indices of the various layers of the
preform) diverge from their design values.

How the diameter is varied during drawing depends on
the preform and to be more precise on the characteristics
of the preform, for example the core radius, the radii of
the deposited layers, the outside radius of the preform

or the indices within the preform. These characteristics
can be measured on a preform on a measurement bench and
using techniques known in the art. For example, the
refractive index profile of the preform can be measured

5   on a PhotoKinetics P104 measurement bench.

The outside diameter and the core diameter of the
preform can be measured, for example. If necessary, the
whole of the index profile of the preform can be
measured. The measurement increment along the preform

10   can be a few centimeters; for conventional methods of
fabricating the preform, variations along the preform in
the core diameter or in other characteristics departing
from their nominal values are small; the above
measurement increment can be sufficient to identify

15   variations in the characteristics of the preform
departing from their design value.

Before drawing, and using conventional simulation
tools on measured geometrical or optical characteristics
of the preform, it is possible to determine the

20   propagation characteristics of the fiber corresponding to
the various sections of the preform and for different
drawing diameters. For example, the geometrical or
optical characteristics of the preform that are measured
can be the core diameter of the fiber and the optical

25   characteristics (the indices and the diameters of the
sections deposited by CVD) of the various parts of the
preform.

The invention proposes to vary the outside diameter
of the fiber to control the propagation characteristics

30   in the fiber. For conventional drawing, fiber diameter
can be varied during drawing in two ways:
         - by modifying the speed of the drawing capstan, or
         - by modifying the rate of descent of the preform.
The first method varies the diameter of the fiber

35   quickly; varying the speed of the capstan typically
modifies the diameter of the fiber by approximately 2%
over a length of fiber of the order of one meter (m) at a

drawing speed of 200 meters per minute (m/min) to
2000 m/min, and is very suitable for varying the fiber
diameter over small distances. The second method varies
the fiber diameter more slowly, and means that a constant
5   drawing speed (capstan speed) can be maintained. A fiber
diameter variation of approximately 2% is typically
obtained over a fiber length of approximately
6 kilometers (km).

The two methods can be combined; thus, it might be
10   sufficient to modify the rate of descent of the preform
to compensate the measured variations; however, it is
also possible to act directly on the speed of the drawing
capstan, to obtain faster control, and then to modify the
rate of descent of the preform while returning to the
15   original drawing speed. This has the advantage of a fast
response to variations combined with maintaining the
normal drawing speed as far as possible.

For a stepped index profile, for example, consider
the situation in which measurements on the preform
20   indicate that the ratio r between the core diameter of
the preform (as defined above) and the outside diameter
of the preform is greater than the design ratio, other
things remaining equal. In this case, for a constant
nominal outside diameter of the fiber, the fiber core
25   diameter is greater than the design diameter; this
increases the chromatic dispersion of the fiber relative
to the design value. The invention therefore proposes to
reduce the outside diameter of the fiber in this
situation; the diameter of the fiber core is also
30   reduced, and approaches the design value. In this case
reducing the outside diameter of the fiber compensates
the variation in the ratio r departing from its nominal
value, the other characteristics of the preform, and in
particular its optical characteristics, conforming to
35   their design values.

Conversely, if the measurements on the preform
reveal that the ratio between the core diameter of the

preform and the outside diameter of the preform is less
than the design ratio, the invention proposes increasing
the outside diameter of the fiber to compensate the
influence on the propagation characteristics of the fiber

5   of the geometrical variations in the preform departing
from its design values.

In the example described above, simulation tools are
used to evaluate the effect of variations in the preform.
Measurements on preforms and corresponding real fibers

10   could also be used for this purpose, and could constitute
a database associating the characteristics of a preform
with the characteristics of the resulting fiber. More
generally, any solution can be used that associates
characteristics of the fiber with variations in the

15   characteristics in the preform departing from design
values in order to calculate the variations to be applied
to the fiber diameter when drawing the preform.

In the simplest case, for a preform of constant
outside diameter, fiber diameter varies relative to its

20   design value in the opposite direction to variation in
the preform core diameter relative to its design value.
The fiber core diameter therefore remains constant or
substantially constant.

More generally, variations in the outside diameter

25   of the fiber can be determined so that the diameter of
the fiber core tends towards a value that compensates as
far as possible for variations in all of the geometrical
or optical characteristics of the preform relative to
design characteristics.

30   If the characteristics of the preform are measured
discretely, the diameter of the fiber can be varied
discretely. Thus, for a measurement pitch of a few
centimeters (cm), it is possible to calculate diameter
values of the fiber in drawing ranges corresponding to a

35   few centimeters of the preform on either side of the
measurement points. The fiber diameter is then varied as
a function of the diameters calculated for these discrete

points, using linear or polynomial interpolation.

Moreover, the invention also proposes to limit the variations in the outside diameter of the fiber; for a nominal diameter of 125 μm, it proposes a maximum diameter variation of ± 2 μm, or a relative variation of $\pm 2\%$. Limiting variations in the diameter of the fiber limits variations in the propagation characteristics and prevents diameter variations having a more harmful effect than departures from the design values induced by the preform. This limit also ensures that the outside diameter remains within the geometrical specifications of the fiber.

Implementations of the invention are described below in the case of a DCF whose propagation characteristics at 1550 nm are as follows:
- chromatic dispersion C: -75 ps/(nm.km),
- chromatic dispersion slope C': -0.5 ps/(nm^2.km),
- effective cross-section: 20 μm^2,
- 2W$_{02}$ mode diameter: 5 μm.

The fiber has a step + ring profile with a nominal core diameter of 15 μm; the preform required has a similar profile. The example considers variations in the core radius A of the preform and in the index Δn of the step.

A first example considers only variations in the core radius A of the preform, with the index profile remaining geometrically similar to the nominal index profile; this variation is given in the first column of the table. In accordance with the invention, it leads to a variation in the fiber diameter of opposite sign.

In the table, the column headed "Δfiber" gives the fiber core variation as a percentage. If the invention is not used, for a $\pm 2\%$ variation of the core radius A, the effective section area varies over the range 19.2 μm^2 to 22.3 μm^2. By controlling the diameter of the fiber in accordance with the invention, within limits of approximately $\pm 2\%$, all the propagation characteristics

can be maintained at their nominal values. The table shows how the propagation characteristics vary when the invention is used. In each case, Δbf and Δaf are respectively the relative departure of the parameter concerned from its nominal value when the invention is not used (with no fiber diameter correction) and when the invention is used (with fiber diameter correction).

The values in the table show that the invention effectively compensates variation in the effective section area S_{eff}, in the chromatic dispersion C, and in the chromatic dispersion slope C'.

	Δ_{fiber} (%)	S_{eff} (μm^2)		C (ps/nm.km)		C' (ps/nm^2.km)	
		Δbf (%)	Δaf (%)	Δbf (%)	Δaf (%)	Δbf (%)	Δaf (%)
A varies by +2%	-2	-4	0	+22.6	0	+18	0
A varies by -2%	+2	+12.5	0	-31	0	-19.4	0

A second example considers only variations in the index Δn of the core of the preform, with all the other parameters fixed. It considers a variation in the fiber diameter such that the effective section area is maintained constant to within ±0.1%. The results obtained are set out in the table below, using the same notation as before.

	Δ_{fiber} (%)	S_{eff} (μm^2)		C (ps/nm.km)		C' (ps/nm^2.km)	
		Δbf (%)	Δaf (%)	Δbf (%)	Δaf (%)	Δbf (%)	Δaf (%)
A varies by +2%	-1.8	-5.4	0	+14	-9	+13	-5.6
A varies by -2%	+2	+8	0	-20.6	+7.5	-21	-1

This table shows that variation in the fiber diameter is of opposite sign to variation in the core index. It also shows that the invention maintains the effective section area constant, although this is achieved at the cost of variations in the chromatic dispersion and in the chromatic dispersion slope; however, those variations are significantly smaller than the corresponding variations if the invention is not used.

A third example considers only variations in the

index Δn of the core of the preform, with all the other
parameters fixed. It considers a variation in the fiber
diameter that maintains the chromatic dispersion constant
to within ±0.1%. The results obtained are set out in the
5   table below, which uses the same notation as before.

	Δ_{fiber} (%)	S_{eff} (μm^2)		C (ps/nm.km)		C' (ps/nm^2.km)	
		Δbf (%)	Δaf (%)	Δbf (%)	Δaf (%)	Δbf (%)	Δaf (%)
A varies by +2%	-1.15	-5.4	-2.4	+14	0	+13	+1
A varies by -2%	+1.45	+8	+1.6	-20.6	0	-21	-7.6

This table shows that variations in the fiber
diameter are of opposite sign to variations in the core
index. It also shows that the invention maintains the
chromatic dispersion constant to within the required
10   limits; as in the previous example, the other propagation
parameters (the effective section area and the chromatic
dispersion slope) vary; however, these variations are
significantly smaller than the corresponding variations
if the invention is not used.

15   A fourth example considers only variations in the
index Δn of the core of the preform, with all the other
parameters fixed. It considers a variation in the fiber
diameter to maintain the chromatic dispersion slope
constant to within ±0.1%. The results obtained are set
20   out in the table below, which uses the same notation as
before.

	Δ_{fiber} (%)	S_{eff} (μm^2)		C (ps/nm.km)		C' (ps/nm^2.km)	
		Δbf (%)	Δaf (%)	Δbf (%)	Δaf (%)	Δbf (%)	Δaf (%)
A varies by +2%	-1.25	-5.4	-2	+14	-1	+13	0
A varies by -2%	+2.1	+8	-0.7	-20.6	+7.5	-21	0

This table shows again that variations in the fiber
diameter are of opposite sign to variations in the core
index. It also shows that the invention maintains the
25   chromatic dispersion slope constant to within the
required limits; as in the previous two examples, the
other propagation parameters (the effective section area
and the chromatic dispersion) vary; once again, these

variations are significantly smaller than the corresponding variations if the invention is not used.

A fifth example considers again variations in the index Δn of the core of the preform, with all the other parameters fixed. This example seeks to maintain the effective section area within ±1% of the nominal value. Accepting greater variations in the effective section area further limits variations in the chromatic dispersion and the chromatic dispersion slope compared to the second example. The results obtained are set out in the table below, which uses the same notation as before.

Δ_{fiber} (%)	S_{eff} (μm^2)		C (ps/nm.km)		C' (ps/nm^2.km)	
	Δbf (%)	Δaf (%)	Δbf (%)	Δaf (%)	Δbf (%)	Δaf (%)
A varies by +2%	-1.6	-5.4	-1	+14	-6	+13	-3.4
A varies by -2%	+1.6	+8	+1	-20.6	+2.3	-21	-6

This table shows that variation in the fiber diameter is of opposite sign to variation in the core index. It also shows that the invention limits variations in the effective section area, chromatic dispersion, and chromatic dispersion slope.

The above examples are representative of various fiber optimization strategies. Other strategies are feasible, depending on the pertinent propagation parameters. The following strategies in particular could be considered:

- determining drawing diameter corrections from measurements on the preform core; this assumes that the outside diameter of the preform is constant and ignores index variations and variations between the ratios of the radii of the deposited layers as far out as the core radius of the preform, it being assumed that the profile is merely enlarged;

- determining drawing diameter corrections from geometrical data of the profile, by measurements on the preform core and measuring the radii of the deposited layers; this assumes that the outside

diameter of the preform is constant;

- determining drawing diameter corrections from geometrical data of the profile, measurements on the preform core, measuring the radii of the deposited layers, and measuring the outside diameter of the preform; and

- determining drawing diameter corrections from geometrical and optical data of the profile, measurements on the preform core, measuring the radii of the deposited layers, measuring the outside diameter of the preform and measuring the indices of the various deposited layers.

The examples also do not consider simultaneous variations in the core diameter and the core index. In practice, if the radius and index of the core both diverge from their nominal value, an optimum solution can be attempted that aims to re-center the three propagation characteristics in the specified ranges as much as possible.

Finally, and very generally, variations in more than one parameter of the index profile can be envisaged. There is an optimum solution, of the same kind as the solution proposed in the fifth example, which aims to re-center the propagation characteristics in given specified ranges as much as possible. The optimum solution is determined as explained above, for example by simulation.

Of course, the present invention is not limited to the examples and implementations described and tabulated, many variants of which will suggest themselves to the skilled person. The variations in the fiber diameter can be determined by methods other than those described hereinabove. Characteristics other than geometrical characteristics can also be considered, and in particular optical characteristics.

The implementations of the invention described above relate to an application in which the effective section area, the chromatic dispersion, or the chromatic

dispersion slope remains constant. The invention applies more generally to compensating the effects on the characteristics of the fiber of variations in the characteristics of the preform departing from their design values, and compensates those effects whether they are constant or not. Thus the invention could also apply to the preforms with decreasing chromatic dispersion values described in WO-A-98 25 861 or to the preforms with discrete and alternating chromatic dispersion values described in EP-A-0 737 873. In all cases, the invention controls the propagation characteristics of the fiber relative to the required propagation characteristics.